RECENT PROGRESS ON THE PHYSICS OF CAPACITIVE DISCHARGES

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OUTLINE

• Dual frequency capacitive discharges
  — Decoupling conditions
  — Stochastic heating
• Ion/neutral energy distributions on the substrate surface
• Dc/rf discharges
  — Electron energy distributions at the substrate
• High frequency electromagnetic effects
  — Standing waves and their control
  — Skin effects
  — 2D finite element method solutions
EVOLUTION OF ETCHING DISCHARGES — FIRST AND SECOND GENERATIONS

FIRST GENERATION
(1 rf source, multi-wafer, low density)

SECOND GENERATION
(2 sources, single wafer, high density)
• In the year 2020
  — 6nm gate width, 6 billion transistors, 73 GHz on-chip clock
  — 14–18 wiring levels (dielectric layers)

• Why capacitive discharge?
  — low surface area seen by plasma (inexpensive)
  — silicon upper electrode (control of F/CF\textsubscript{x} ratio)
  — robust uniformity over wide pressure range
DUAL FREQUENCY CAPACITIVE DISCHARGES
WHY DUAL FREQUENCY CAPACITIVE DISCHARGES?

- Independent control of ion flux and ion energy

| High frequency power $P_h$ controls ion flux |
| Low frequency voltage $V_l$ controls ion energy |


- $R \sim 15$–30 cm, $L \sim 1$–3 cm
- $p \sim 30$–300 mTorr, $C_4F_8/O_2/Ar$ feedstock
- $f_h \sim 27.1$–160 MHz, $V_h \sim 50$–200 V
- $f_l \sim 2$–13.56 MHz, $V_l \sim 500$–1500 V
- Absorbed powers $P_h, P_l \sim 500$–3000 W
IDEAL DECOUPLING CONDITIONS

- Plasma density \( n \propto \) electron power \( P_e \)

Total power absorbed: \( P_{\text{abs}} = P_e \left(1 + 0.4 \frac{V_{\text{rf}}}{E_c + E_e'}\right) \)

\( V_{\text{rf}} = \) source voltage, \( E_c + E_e' = \) electron energy lost/e-i pair created

— Only high frequency source supplies electron power

\[ \omega_h^2 V_h^{1/2} \gg \omega_l^2 V_l^{1/2} \]

— High frequency source only supplies electron power

\( V_h \ll 2.5(E_c + E_e') \)

- Dc sheath voltage \( \bar{V} \propto V_h + V_l \) (+ small crossterm)

— Low frequency source sets sheath voltage

\( V_l \gg V_h \)
DUAL FREQUENCY STOCHASTIC HEATING

- An important electron heating process below 200 mTorr

- How are electrons heated by the high frequency oscillations?

STOCHASTIC HEATING POWER

• Hard wall theory in dual frequency regime:

\[
S_{\text{stoc}} = \frac{1}{2} \frac{m \bar{v}_e}{e^2 n_s} \frac{J_h^2}{e^2 n_s} \times \left(1 + \frac{\pi}{4} H_l\right) \left(\frac{H_l}{H_l + 2.2}\right)
\]

High freq part \quad Low freq part \quad F(H_l)

\( S_{\text{stoc}} = \) stochastic heating power per unit electrode area
\( m = \) electron mass
\( \bar{v}_e = (8eT_e/\pi m)^{1/2} = \) mean thermal electron speed
\( J_h = \) high frequency current density
\( n_s = \) plasma density at bulk plasma–sheath edge
\( H_l = 0.55(V_l/T_e)^{1/2} = \) low frequency enhancement factor

• Fluid theory gives similar result
PARTICLE-IN-CELL SIMULATIONS

- Dual frequency stochastic heating

![Graph showing F(H₁) vs H₁ with data points for different theories: Hard wall theory, PIC (mobile ions), PIC (fixed ions), Fluid theory.]

- Ohmic heating in the sheath shows similar behavior
ION/NEUTRAL ENERGY DISTRIBUTIONS ON THE SUBSTRATE SURFACE

FORMATION OF PERIOD-AVERAGED IED FOR SINGLE-FREQUENCY SHEATH

\[
\tau_i = \text{ion transit time across the sheath}
\]

- For \(\omega \tau_i \ll 1\), ions respond to the full time-varying sheath voltage
- For \(\omega \tau_i \gg 1\), ions respond to the time-average sheath voltage
  \[\Rightarrow\text{low-pass filter}\]
ION ENERGY DISTRIBUTION (IED)

- What is energy distribution of ion flux incident on the substrate?
- Collisionless ions with two and three frequencies

\[
\begin{align*}
\text{Sheath voltage} & \rightarrow V_s(t) & \text{Voltage seen by ions} & \rightarrow V_i(t) \\
\text{Fourier transform} & \rightarrow V_s(\omega) & \text{Apply filter } \alpha(\omega) & \rightarrow \text{IEDF} \\
\text{Inverse Fourier transform} & \rightarrow |dV_i/dt|^{-1}
\end{align*}
\]

- Use filter \( \alpha(\omega) = [(c\omega \tau_i)^p + 1]^{-1/p} \) with \( c = 0.3, \ p = 5, \) and \( \tau_i = \text{ion transit time across the sheath} = 3\bar{s}(M/2eV_s)^{1/2} \)

(P.A. Miller and M.E. Riley, *J. Appl. Phys.* 82, 3689, 1997 uses filter with \( c = 1, \ p = 2 \))
DUAL/TRIPLE FREQUENCY PIC SIMULATIONS

Gap=3 cm
p=30 mTorr
Collisionless ions

400V/64MHz
800V/3MHz

400V/64MHz
800V/2MHz

400V/64MHz
800V/8MHz
800V/2MHz

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COLLISIONS WITH/AMONG NEUTRALS
(40 V at 64 MHz, 50 mTorr argon, 3 cm gap)

- Fast computational model for neutral energy distribution (NED)

(with A. Wu and J.P. Verboncoeur)

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**DC/RF DISCHARGES**


MOTIVATIONS FOR ADDING DC SOURCE

- “Tune” discharge particle and energy balance
  \( \Rightarrow T_e \downarrow, n_e \uparrow, \) radial uniformity
- “Tune” secondary electron bombardment of substrate
  (etch selectivities, charging damage)

**DIODE**
(for 1D PIC simulations)

**TRIODE**
(for industrial use)
COMPARISON TO PIC SIMULATIONS

- Symmetric (1D planar) diode discharges

(Symbols — PIC with pressure in mTorr; lines — theory)

- Asymmetric (1D cylindrical) diode discharges also give good agreement with DC/RF sheath theory
— Transit time across gap $\tau_{fr} = d/\nu_h$ at low pressures
— Diffusion time $\tau_{\text{diff}} = d^2/2D_h$ at higher pressures ($D_h = \lambda_h \bar{v}_h/3$)
— Trapping time $\tau_{\text{trap}} = \delta/f$ (favorable configuration of rf voltages can trap secondaries for a fraction $\delta$ of the rf period $1/f$)
— Collisional energy loss time $\tau_{izh}^*$ (secondary electrons lose energy and join the thermal population)

\[ \varepsilon_h = 70 \text{ V}, \delta = 0.5 \]
Secondary electrons are ballistic and have high energies for DC/RF case.
HIGH FREQUENCY ELECTROMAGNETIC EFFECTS
STANDING WAVES AND SKIN EFFECTS

- High frequency and large area ⇒ standing wave effects
- High frequency ⇒ high density ⇒ skin effects

Consider only the high frequency source

Fields cannot pass through metal plates

(1) $V_s$ excites radially outward wave in top vacuum gap
(2) Outward wave excites radially inward wave in plasma
SURFACE WAVE MODE

- Power enters the plasma via a *surface wave mode*:

\[
\text{Surface Wave Mode}
\]

- Radial wavelength for surface wave (low density limit):

\[
\lambda \approx \frac{\lambda_0}{\sqrt{1 + d/s}} \sim \frac{\lambda_0}{3}
\]

with \( \lambda_0 = c/f \) the free space wavelength.

- Axial skin depth for surface wave:

\[
\delta \sim \frac{c}{\omega_p}
\]

- There are also *evanescent modes* leading to edge effects near \( r = R \)
STANDING WAVE EFFECT — FIXED $n_e$ AND $s$

- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm, $n_e = 10^9$ cm$^{-3}$, $\delta \approx 16$ cm
- $P_{\text{cap}}$ (dash), $P_{\text{ind}}$ (dot) and $P_{\text{tot}}$ (solid) as a function of $r$

13.56 MHz ($\lambda \approx 9$–10 m)  40.7 MHz ($\lambda \approx 3$ m)

Small standing wave and skin effects  Large standing wave effect; center-high profile
EXPERIMENTAL RESULTS FOR STANDING WAVES

20×20 cm discharge

\( p = 150 \text{ mTorr} \)

50 W rf power

The standing wave effect is seen at 60 MHz and is more pronounced at 81.36 MHz

SKIN EFFECTS — FIXED $n_e$ AND $s$

- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm, $f = 13.56$ MHz, $\lambda \approx 9$ m
- $P_{\text{cap}}$ (dash), $P_{\text{ind}}$ (dot) and $P_{\text{tot}}$ (solid) as a function of $r$

**$n_e = 10^9$ cm$^{-3}$ ($\delta = 16.7$ cm)**

**$n_e = 10^{10}$ cm$^{-3}$ ($\delta = 5.3$ cm)**

![Graphs showing power density as a function of radius for different $n_e$ values.](image)

**Small standing wave and skin effects**

**Large skin effects; center-low profile**
FINITE ELEMENT METHOD (FEM), 2D EM SOLUTIONS
(with Insook Lee and D.B. Graves)

- Arbitrary (asymmetric) discharge geometries and materials
- Transition from global to local power balance
- Distinguish edge effects (electrostatic) versus EM effects
- Series resonance stop band

Solution Procedure

(Analytical model: collisional Child law, variable sheath width, stochastic and ohmic heating in the sheath)
STANDING WAVES — 40 W, 150 mTorr

- Edge effect
- Standing wave effect

- 13 MHz
- 60 MHz
- 80 MHz
- 100 MHz
SKIN EFFECTS — 150 mTorr

FEM model
(with Insook Lee and D.B. Graves)

Transmission line model

- Transmission line model: collisionless sheaths, no edge effects, purely local power deposition

In both cases spatial E to H transitions are seen
ASYMMETRIC (BOTTOM) EXCITATION — 150 mTORR

\[ H_\phi = K/r \]

Frequency: 150 mT

13 MHz
40 W
708 V
4.78 H

10^10 Electron density

Reduced edge effect

80 MHz
40 W
44.6 V
1.03 H

10^10 Electron density

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ASYMMETRIC VOLTAGE WAVEFORMS

\[ H_\varphi = K/r \]

\[ V_\text{rf (including bulk)} \]

\[ V_1 \text{ (bottom)} \]

\[ V_1 \text{ (top)} \]

Voltage asymmetry disappears
NONLINEAR EFFECTS IN CAPACITIVE DISCHARGES

- An active area of research

CONCLUSIONS

- Third generation capacitive reactors for dielectric etch will dominate the fab
- Capacitive reactor research and development must intensify to meet this need